# DECOMPOSITION OF FOREST LITTER AND THE CYCLE OF ELEMENTS IN AN OAK FOREST

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There are two distinct periods in the annual cycle of an oak forest. The first is the time of formation of the forest litter under the influence of autumn defoliation. In the oak forest of the Voronezh State Reservation, where we made our investigation, leaf-fall begins at the end of August and ends in early November.[1] The second period, which embraces the other months of the year, is the time when the fallen leaves decompose.

Long-term investigations showed that the mass of foliage forming in an oak forest every year does not change in relation to the age of the tree stand. Weather conditions in individual years have a much greater effect (2, 3, 4). Data on the amount of litter in a sedge-goutweed oak forest show essential differences in the mass of litter forming annually. This influence manifests itself differently in plot areas in oak stands of different ages (Table 1).

Depending on the fluctuations in the mass of litter, the amount of nutrient elements which return to the soil surface with the litter also changes. This can be illustrated by data for a 93- to 106-year old oak stand, where the difference in age has the least effect, and the observed fluctuations in the amount of litter are caused primarily by weather conditions (Table 2).

The alternation in the annual cycle of the litter formation and its subsequent decomposition determines the change in the mass of forest litter. The amount of litter in an oak forest is greatest at the beginning of spring and consists of undecomposed old litter and litter accumulated during the autumn and partly during the winter-spring season. The forest litter decomposes during the following spring-summer season and by the time autumn leaf-fall occurs the mass of litter reaches its lowest value. The change in the mass of litter from 1957-1958 can serve as an example. After autumn leaf-fall, supplemented by the spring leaf-fall of late oak, the total amount of forest litter was 13.2 metric tons/ha. Decomposition in summer reduced this amount at the beginning of the next leaf-fall to 9.7 metric tons/ha. The difference of 3.5 metric tons/ha corresponds approximately to the leaf-fall.

Both changes in the mass of litter and in the rate of its mineralization depend on weather conditions. Generally, however, the decomposition of litter corresponds more or less to the accumulation of litter, with unavoidable deviations in one or the other directions. For the sake of comparison we must mention that the amount of forest litter in pine stands in the same forest massive is 37-46 metric tons/ha.

Two layers can be distinguished in the composition of forest litter in an oak forest. The largest mass fluctuations occur in the upper layer, which consist of fallen leaves and is designated by the letter L. The weight of this layer was 5.3 metric tons/ha in the spring of 1958, while it decreased to 2.7 metric tons/ha, i. e., by 2.6 metric tons/ha, at the beginning of leaf-fall. Mass fluctuations in the second layer (or fermentation layer), which we will designate by the letter F, were smaller. This layer consists of almost completely decomposed leaves of a dark brown color, which are interwoven with the mycellia of fungi. The entire F layer weighed 7.9 metric tons/ha in spring, while before leaf-fall its weight became 6.9 metric tons/ha, i. e., its mass was reduced by 1.0 metric tons/ha.

As the mass of the layers of forest litters decreases, the content of ash elements in them increases because of the decomposition of organic compounds, primarily carbohydrates. We found an increase in the content of ash elements in the L layer from 5.2% to 6.5% from spring to autumn; the increase in the F layer was from 8. 2% to 9.4%.

As compared to the fallen leaves (Table 3) the forest litter becomes poor in nitrogen, potassium, phosphorus, and magnesium and relatively rich in silica, aluminum, and iron, and slightly less in calcium as it decomposes. This is especially noticeable at the fermentation layer (F), where the decrease in potassium is most pronounced.

Additional patterns are revealed by the calculation of the total content of elements in the forest litter (in kg/ha) and its separate layers

[1] There is also a leaf-fall in spring in stands containing late oak, which keeps its dry leaves until spring.

Table 1

Dynamics of litter fall in a sedge-goutweed oak forest on dark gray-brown sandy loam forest soils

| Age of the stand | Years of observation, metric tons/ha | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1948 | 1949 | 1950 | 1951 | 1952 | 1953 | 1954 | 1955 | 1956 | 1957 | 1958 | 1959 | 1960 |
| 12—24 | 2,8 | 3,5 | 4,3 | 4,6 | 3,3 | 3,7 | 4,2 | 3,7 | 4,1 | 3,4 | 4,2 | 3,8 | 3,2 |
| 48—60 | 3,3 | 4,1 | 4,0 | 4,1 | 3,7 | 4,1 | 4,9 | 3,8 | 4,7 | 4,3 | 3,9 | 4,1 | 3,5 |
| 93—106 | 3,1 | 2,8 | 4,0 | 4,9 | 4,3 | 4,6 | 5,5 | 4,4 | 5,3 | 4,6 | 4,4 | 4,0 | 4,0 |
| 130—142 | — | 3,8 | 4,9 | 4,2 | 4,2 | 3,9 | 5,4 | 4,8 | 5,1 | 3,4 | 4,7 | 5,1 | 3,6 |

Note: Comma represents decimal point.

Table 2

Amount of nitrogen and ash elements from the leaf-fall (leaves) in a 93- to 106- year old sedge-goutweed oak stand

| Years litter collected | N | Si | Al+Fe | Ca | Mg | K | P | S |
|---|---|---|---|---|---|---|---|---|
| | kg/ha per year | | | | | | | |
| 1948 | 32,9 | 18,6 | 3,8 | 57,0 | 8,9 | 21,0 | 4.9 | 4,8 |
| 1949 | 30,6 | 17,1 | 3,5 | 54,5 | 7,7 | 19,6 | 4,6 | 4,7 |
| 1950 | 42,8 | 22,1 | 4,6 | 72,5 | 10,4 | 25,8 | 6,1 | 6,0 |
| 1951 | 54,9 | 27,7 | 5,6 | 95,5 | 12,5 | 33,9 | 8,2 | 8,4 |
| 1952 | 46,3 | 22,2 | 5,1 | 74,7 | 10,7 | 25,6 | 6,2 | 6,1 |
| 1953 | 43,9 | 21,5 | 5,0 | 80,8 | 11,6 | 27,6 | 6,7 | 6,6 |
| 1954 | 54,2 | 27,5 | 5,8 | 95,6 | 13,4 | 33,3 | 7,9 | 7,7 |
| 1955 | 43,2 | 24,0 | 4,1 | 72,3 | 10,8 | 25,2 | 6,0 | 4,9 |
| 1956 | 48,6 | 26,2 | 4,8 | 81,0 | 12,1 | 28,2 | 6,7 | 6,7 |
| 1957 | 46,0 | 23,9 | 4,3 | 77,3 | 11,2 | 26,9 | 6.6 | 6,4 |
| 1958 | 43,2 | 24,0 | 4,1 | 72,3 | 10,8 | 25,2 | 6,0 | 4,9 |
| 1959 | 30,9 | 21,0 | 3,1 | 59,3 | 9,0 | 14,2 | 9,9 | 4,9 |
| 1960 | 37,5 | 25,5 | 3,7 | 72,0 | 10,9 | 17,2 | 11,9 | 6,0 |

Note: Comma represents decimal point.

(Table 4). Such a calculation shows that the total content of iron in the forest litter hardly changes during decomposition and the aluminum content decreases only slightly; the decrease in the amount of silicon is more pronounced. The improverishment of the litter is greatest

Table 3

Content of nitrogen and ash elements in fallen leaves and in the litter of an oak forest, 1958

| Sampling time | Layers | N | Si | Al | Fe | Ca | Mg | K | P |
|---|---|---|---|---|---|---|---|---|---|
| | Litter | In % of substance dried at 100 °C | | | | | | | |
| | | 1,95 | 0,45 | 0,03 | 0,04 | 1,64 | 0,22 | 0,45 | 0,17 |
| June | L | 1,81 | 0,53 | 0,29 | 0,13 | 0,70 | 0,14 | 0,20 | 0,16 |
| Same | F | 0,64 | 0,81 | 0,45 | 0,20 | 1,88 | 0,21 | 0,11 | 0,09 |
| July | L | 1,70 | 0,55 | 0,32 | 0,16 | 1,62 | 0,16 | 0,17 | 0,14 |
| Same | F | 1,52 | 0,84 | 0,49 | 0,25 | 1,82 | 0,17 | 0.09 | 0,08 |
| August | L | 1,63 | 0,57 | 0,37 | 0,18 | 1,41 | 0,14 | 0,14 | 0,13 |
| Same | F | 1,46 | 0,87 | 0,52 | 0,27 | 0,90 | 0,17 | 0,07 | 0,07 |

Note: Comma represents decimal point.

Table 4

Change in the content of nitrogen and ash elements in the litter of an oak forest

| Sampling time | Layers | N | Si | Al | Fe | Ca | Mg | K | P |
|---|---|---|---|---|---|---|---|---|---|
| | | Content in kg/ha | | | | | | | |
| June | L | 96,3 | 28,2 | 15,4 | 6,9 | 90,4 | 7,4 | 10,6 | 8,5 |
| | F | 129,9 | 64,2 | 35,6 | 15,8 | 148,9 | 16,6 | 8,7 | 7,1 |
| | Total | 226,2 | 92,4 | 51,0 | 22,7 | 239,3 | 24,0 | 19,3 | 15,6 |
| July | L | 57,1 | 18,5 | 10,8 | 5,4 | 54,4 | 5,4 | 5,7 | 4,7 |
| | F | 103,4 | 57,1 | 33,3 | 17,0 | 123,8 | 11,6 | 6,1 | 5,4 |
| | Total | 160,5 | 75,6 | 44,1 | 22,4 | 178,2 | 17,0 | 11,8 | 10,1 |
| August | L | 44,7 | 15,6 | 10,1 | 4,9 | 38,6 | 3,8 | 3,8 | 3,6 |
| | F | 101,6 | 60,6 | 36,2 | 18,8 | 132,2 | 11,8 | 4,9 | 4,9 |
| | Total | 146,3 | 76,2 | 46,3 | 23,7 | 170,8 | 15,6 | 8,7 | 8,5 |

Note: Comma represents decimal point.

in potassium, nitrogen, and phosphorus, and somewhat less in calcium and magnesium. The largest decrease in the amount of these elements in 1958 occurred in June-July and was relatively small in August.

If we calculate the content of each element in August (in percent) from that in June, we obtain the following ascending series in order of mobility:

| mobility | Fe | < Al | < Si | < Ca | < Mg | = N | < P | < K |
|---|---|---|---|---|---|---|---|---|
| % of initial | 100 | 90 | 83 | 72 | 65 | 65 | 53 | 46 |

The absolute values of the series change in other years, but the relative order of mobility remains the same.

The foregoing analytical material does not embrace the early spring period, when leaching of the forest litter and soil by snow meltwater and spring rains is greatest. Therefore it cannot characterize the absolute loss of separate elements by the forest litter.

Moreover, this material does not show where the elements lost by the forest litter go. We cannot tell on the basis of the foregoing analyses which part of the elements was leached from the litter by precipitation, which was removed by animals feeding on dead plant materials, and which was drawn into the new biological cycle. A certain part of the elements supplied to the forest litter during the biological cycle is later undoubtedly removed from the litter into the soil. This process has an exceptionally great effect on the formation of the profile of forest soils and their forest-growing properties.

Calculations of the elementary composition of parent rocks in volumetric percentages showed that 92%-94% of their volume is occupied by oxygen atoms, while all the remaining atoms account for 6%-8%. Thus, the elements needed by plants are very scattered among oxygen atoms in rocks. As a rule, there is no nitrogen in rocks. It follows from the foregoing that unchanged parent rocks represent a medium which is unfavorable for nutrition.

The upper part of the soil profile becomes enriched with humus, nitrogen, and ash elements during the biological cycle. This changes the soil medium inhabited by plants considerably. The concentration of biologically important elements in the root zone, which is achieved through the forest litter, creates more favorable conditions for the development of forest vegetation and improves the forest-growing properties of soil.

The upper part of the soil profile in the foregoing oak forests on poor quartz sand is noticeably enriched not only with humus and nitrogen, but also with aluminum, iron, manganese, calcium, magnesium, sulfur, and phosphorus. The accumulation of calcium and sodium is less pronounced. This enrichment of the upper part of the profile with the foregoing elements (Table 5) takes place at the expense of the underlying layer (D horizon, sample from a depth of 122-128 cm), which is richer in ash elements, during the biological cycle of elements. Elements brought by the temporary water table can also be drawn into the biological cycle in spring.

Not only the foregoing elements, but also a small amount of microelements is drawn into the biological cycle. An analysis of fallen oak leaves (Table 6) showed that a considerable amount of titanium, a considerably smaller amount of strontium, and even a smaller amount of the remaining elements (vanadium, chromium, nickel, copper, and lead) enters the soil with them. An especially small amount of cobalt and molybdenum is supplied to the soil by the fallen leaves, while the amount of zinc and tin is below the sensitivity of the spectral method.

A comparison of the content of microelements in the fallen leaves and in the forest litter gives a certain idea of the process of microelements accumulation in the forest litter. The accumulatic

Table 5

Results of total chemical analysis of dark gray-brown, sandy loam forest soil underlain by silty clay loam. Sedge-goutweed oak stand (Ye. N. Plastinina, analyst)

| Horizon | Depth, cm | Si | Al | Fe | Mn | Ca | Mg | K | Na | S | P | Oxygen difference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | In % of ignited soil | | | | | | | | | | |
| $A_1$ | 0— 5 | 44,86 | 1,00 | 0,44 | 0,06 | 0,51 | 0,16 | 0,25 | 0,16 | 0,05 | 0,03 | 52,48 |
| $A_1$ | 5— 10 | 44,79 | 0,67 | 0,52 | 0,04 | 0,47 | 0,16 | 0,28 | 0,16 | 0,09 | 0,03 | 52,79 |
| $A_1B_1$ | 18— 23 | 45,25 | 0,39 | 0,35 | 0,04 | 0,19 | 0,22 | 0,20 | 0,16 | 0,04 | 0,01 | 53,05 |
| $B_2$ | 54— 59 | 45,31 | 0,08 | 0,39 | 0,02 | 0,15 | 0,07 | 0,24 | 0,13 | 0,03 | 0,01 | 52,97 |
| $B_3$ | 78— 83 | 45,50 | 0,40 | 0,26 | 0,01 | 0,20 | 0,07 | 0,18 | 0,08 | 0,06 | 0,01 | 53,23 |
| D | 122—128 | 39,27 | 4,53 | 2,29 | 0,03 | 0,52 | 0,36 | 0,90 | 0,23 | 0,06 | 0,04 | 51,77 |

Note: The first sample ($A_1$ 0-5 cm) was taken immediately from under the litter.
Note: Comma represents decimal point.

Table 6

Content of microelements in fallen oak leaves and in the litter of an oak forest (M. A. Vinnik, analyst)[a]

| Subject of analysis | Ash, % | Ti | V | Cr | Ni | Co | Mo | Cu | Zn | Sr | Pb | Sn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | In mg per 1 kg of substance dried at 100°C | | | | | | | | | | |
| Fallen leaves | 5.27 | 152,8 | 4,8 | 5,3 | 4,7 | 0,3 | 0,4 | 4,9 | — | 15,2 | 1,6 | — |
| L layer | 9,79 | 330.8 | 10,7 | 13,6 | 0,3 | 0,7 | 0,9 | 9,2 | — | 28,2 | 3,0 | — |
| F layer | 21.14 | 207,2 | 9,5 | 18,0 | 4,7 | — | 1,4 | 20,1 | — | 61,3 | 3,2 | — |

[a]The determinations were made on an ISP-22 spectrograph and were followed by measurements of the darkening of spectral lines on the microphotometer by the method of three standards. The sign — (minus) indicates that the content of the given element is below the sensitivity of the method. The litter samples were taken in August, 1957.
Note: Comma represents decimal point.

of titanium, strontium, vanadium, chromium, and copper is very distinct. Lead and molybdenum accumulate to a much lesser degree. The content of zinc and tin is below the sensitivity of the spectral method both in the fallen leaves and in the litter.

The content of all microelements investigated, except titanium, was minimal in the parent material (quartz sand) (Table 7). As was to be expected, the underlying material — silty clay loam, was richer in microelements. However, the content of molybdenum, zinc, strontium, tin, and lead in it was approximately the same as in the quartz sand. The difference being in the higher content of titanium, vanadium, chromium, manganese, nickel and to a lesser degree cobalt. Under these conditions the root systems of oak and its companions had to work hard to concentrate in the upper part of the soil profile the biologically important microelements which are very scattered in the soil-forming parent material and the underlying material.

In spite of such poor availability of microelements to vegetation, analyses (Table 7) show the accumulation of a number of microelements in the humus-accumulation horizon ($A_1$); accumulation is less pronounced in the lower-lying horizons (AB and $B_1$). The accumulation of titanium and manganese is most distinct, that of vanadium, chromium, nickel, and copper is much less pronounced, and there is very little cobalt and zinc. The behavior of strontium is peculiar. Even though it is contained in noticeable amounts in the fallen leaves and concentrates in the litter, its content in the upper soil horizons was not high.

The course of litter decomposition is very important for the supply of nutrients in the available form to forest vegetation. Soil and litter animals have an essential influence on the decomposition rate of fallen leaves. This is evidenced by the very large number of gnawed leaves composing the upper layer of the forest litter. It was noted that gnawed leaves are the first to be decomposed by microorganisms. Broadleaf forests are especially rich in soil and litter fauna. The discussion of this wide and complicated problem does not enter into the frame of the present communication.

Microbiological investigations made by Chastukhin in the foregoing oak forests (5) showed that recently fallen leaves are already covered with numerous black spots from the fruiting

Table 7

Microelement content in dark gray-brown sandy loam soil on quartz sand underlain by silty clay loam. (M. A. Vinnik, analyst).

| Horizon | Depth, cm | Ti | V | Cr | Ni | Co | Mo | Cu | Zn | Sr | Sn | Pb | Mn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | In mg per 1 kg of soil ignited at 450°C | | | | | | | | | | | |
| $A_1$ | 1—10 | 5200 | 56 | 45 | 28 | 7 | <5 | 37 | 500 | <100 | <5 | <5 | 3300 |
| AB | 16—23 | 2800 | 30 | 48 | 9 | 5 | <5 | 30 | <100 | <100 | <5 | <5 | 790 |
| $B_1$ | 26—36 | 1900 | 28 | 52 | 8 | <5 | <5 | 31 | <100 | <100 | <5 | <5 | 100 |
| $B_2$ | 45—55 | 500 | 10 | 39 | 6 | <5 | <5 | 26 | <100 | <100 | <5 | <5 | 100 |
| $B_3$ | 80—90 | 810 | 22 | 34 | 8 | <5 | <5 | 25 | <100 | <100 | <5 | <5 | 100 |
| D | 120—130 | 4800 | 79 | 45 | 17 | 7 | <5 | 35 | <100 | <100 | <5 | <5 | 270 |

bodies of ascomycetous fungi. Thus, the fungal action begins in a number of cases on leaves which are still attached to the tree. Chastukhin found the mycelium of basidium fungi and cellulose-decomposers (Trichoderma ligno, etc.) developing in the slightly decomposed (upper) layers of forest litter. In addition to basidium fungi he found strongly developing molds in the lower layer of the litter. Experiments on the decomposition of cellulose substantiated the fungal nature of this process in the oak forests studied.

To study the release and removal of nitrogen and ash elements from the forest litter, we used Büchner-type funnels, used for this purpose in the past by N. N. Stepanov and others. By placing leaves or litter with an undisturbed structure into this funnel we could analyze the composition of the percolate. A number of observations made during the work process lead us to the conclusion that the mineralization of the leaves or litter, taken individually, differs from that taking place when they are in contact with the soil.

To clarify this problem, Ye. M. Samoylova made an additional experiment in the autumn of 1958 on the decomposition of leaves under conditions more close to natural conditions. This experiment was made parallel to the study of the decomposition of litter in the funnels. Caprone bags were filled with oak and basswood leaves and placed on the soil surface in an oak-basswood stand. The walls of the bags were perforated to let the litter fauna through. The experiment was replicated 5 times, the agreement between the parallel experiments being good.

A comparison of the decomposition rate in the funnels and in the bags gave the following results, showing the decrease in weight in the course of a year in percent of initial weight:

| Leaves: | Oak | Basswood |
|---|---|---|
| in funnels | 16 | 37 |
| in bags | 27 | 60 |

Thus, the decomposition rate in the funnels was 1.6-1.8 times slower than in the bags. This shows that we cannot judge the loss of elements from the soil and draw any genetic conclusions from this on the basis of the difference in the removal of elements only from the litter and litter — soil, placed in lysimeters. The greatest decrease in weight took place during the spring-summer period, it was less in autumn, and very small (2%) in winter.

During the investigations we could observe regular differences in the nature and decomposition rate of the leaves of various trees. A relation was found between the rate of leaf mineralization and the content of nitrogen and ash elements in the leaves (4, 6). Decomposition by lower organisms, which possess a selective ability with respect to the nutrient substrate, is the more rapid the richer the leaves are in the foregoing elements. A role is also played by other properties of the leaves, such as hardness, the content of tannic substances, etc.

Basswood, ash, hazelnut, and elm leaves decompose most rapidly, since they constitute a favorable substrate for soil and litter animals and microorganisms. Oak and aspen leaves were found to be most resistant to decomposition. Oak and aspen leaves decompose more rapidly when mixed with hazelnut, ash, and basswood leaves.

According to anatomical investigations (4), the mesophyll is decomposed first and then the epidermis and a large portion of small cells. The leaf veins are preserved longest. Chemical analyses showed a considerable decrease in the content of protein, bitumen, and hemicellulose and a slightly lesser decomposition of cellulose during the winter and early spring periods. At the same time there was a considerable accumulation of water-soluble organic substances. During the following summer-autumn period cellulose decreased further and the content of water-soluble organic compounds decreased sharply. At the same time re-synthesis of hemicellulose took place and the amount of non-hydrolyzable residue increased as a result of the formation of humic substances.

The analytical material on the removal of ash elements from decomposing leaves obtained for a number of years (1950-1960) is so erroneous that we cannot present it here. This limits us to the presentation of our final general conclusions.

Potassium is released most rapidly during the decomposition of leaves. Under the conditions of lysimetric experiments, basswood leaves lost more than 90% of the initial amount of potassium each year; elm and hazelnut leaves lost 85%; ash, maple, and oak leaves lost 80%. The foregoing amounts of potassium were removed from the leaves of many trees as early as during the early spring period. The removal of sulfur, phosphorus, and magnesium was considerably slower, and that of calcium was even slower than that. Oak, ash, basswood, and hazelnut leaves lost 40%-50% of their initial calcium content in the course of a year. As in other investigations, there was a relative accumulation in the products of leaf decomposition of silicon, aluminum, and iron, which are removed most slowly from the leaves.

The amount of elements removed beyond the soil profile was assessed in a special experimental plot of 35 m² for the study of horizontal flow. The description of this plot is given in an earlier publication (2), which included data for the first 4 years of observation (1954-1957). Now we can present data for 7 years (1954-1960).

In all these years horizontal moisture flow took place only during the snow melting period during the second half of March and April, sometimes extending to the first half of May. In 1957 slight percolation was observed in the second half of February because of a prolonged warm spell in winter. There was some percolation amounting to a total of 2.5 metric tons/ha in the rainy summer of 1958. The total annual percolation during 7 years varied from 15 metric tons/ha (1960) to 60 metric tons/ha (1958). Fluctuation in the flow depends on the spring storage of moisture in soil, moisture content of snow cover at the beginning of snow thaw, manner of thawing and effect of

Table 8

Relationship between the supply of elements from the litter and their removal by percolation in a sedge-goutweed oak stand

| Supply and removal of elements | Si | Al | Ca | Mg | K | P | S | N |
|---|---|---|---|---|---|---|---|---|
| 1953-1954 | | | | | | | | |
| Supplied by litter, kg/ha | 35,4 | 5,5 | 97,5 | — | 42,5 | 8,7 | — | 50,9 |
| Removed by percolation, kg/ha | 0,034 | 0,147 | 3,277 | — | 0,208 | Trace | — | — |
| Same, % of supply | 0,10 | 2,67 | 3,36 | — | 0,49 | 0 | — | — |
| 1954-1955 | | | | | | | | |
| Supplied by litter, kg/ha | 34,8 | 5,7 | 100,9 | — | 42,8 | 8,7 | — | 50,3 |
| Removed by percolation, kg/ha | 0,013 | 0,295 | 2,761 | — | 0,093 | Trace | — | — |
| Same, % of supply | 0,04 | 5,17 | 2,74 | — | 0,22 | 0 | — | — |
| 1955-1956 | | | | | | | | |
| Supplied by litter, kg/ha | 29,0 | 5,5 | 83,9 | — | 35,6 | 7,4 | — | 42,4 |
| Removed by percolation, kg/ha | 0,019 | 0,528 | 4,013 | — | 0,709 | Trace | — | 0,752 |
| Same, % of supply | 0,07 | 9,60 | 4,78 | — | 1,96 | 0 | — | 1,78 |
| 1956-1957 | | | | | | | | |
| Supplied by litter, kg/ha | 24,8 | 3,3 | 72,6 | — | 26,5 | 6,6 | — | 42,1 |
| Removed by percolation, kg/ha | 0,09 | 1,334 | 1,384 | — | 0,253 | 0,003 | — | 0,415 |
| Same, % of supply | 0,37 | 39,39 | 1,19 | — | 0,95 | 0,05 | — | 0,99 |
| 1957-1958 | | | | | | | | |
| Supplied by litter, kg/ha | 24,6 | 3,2 | 54,4 | 8,5 | 23,8 | 4,4 | 4,1 | 35,2 |
| Removed by percolation, kg/ha | 0,05 | 0,12 | 2,21 | 0,21 | 0,09 | 0,009 | 0,05 | 0,71 |
| Same, % of supply | 0,21 | 3,8 | 4,1 | 2,5 | 0,4 | 0,2 | 1,2 | 2,0 |
| 1958-1959 | | | | | | | | |
| Supplied by litter, kg/ha | 22,6 | 2,9 | 49,8 | 7,7 | 21,7 | 4,6 | 3,8 | 31,9 |
| Removed by percolation, kg/ha | 0,27 | 0,17 | 0,99 | 0,10 | 0,02 | 0,001 | 0,006 | 0,18 |
| Same, % of supply | 1,2 | 5,9 | 2,0 | 1,3 | 0,009 | 0,02 | 0,16 | 0,6 |
| 1959-1960 | | | | | | | | |
| Supplied by litter, kg/ha | 29,3 | 3,5 | 80,4 | 11,3 | 30,0 | 10,5 | 5,6 | 36,2 |
| Removed by percolation, kg/ha | 0,11 | 0,006 | 0,33 | 0,03 | 0,02 | 0,002 | 0,007 | 0,08 |
| Same, % of supply | 0,37 | 0,17 | 0,41 | 0,27 | 0,07 | 0,02 | 0,13 | 0,22 |

Note: Comma represents decimal point.

spring rains.

The active reaction of all the percolation waters during these years was close to neutral, varying from 6.9-8.0. Of all the elements, calcium was removed in the greatest amounts during all these years, while much less potassium was removed (Table 8). For magnesium we have data only for the last 3 years which show that magnesium is removed in much lesser amounts than calcium. Only very insignificant, sometimes unassessable amounts of phosphorus were removed; the removal of sulfur was also small, but greater than phosphorus. The considerable removal of aluminum when percolation waters contained a small amount of silicon, was unexpected. The removal of silicon increased considerably in the last two years (1959, 1960), exceeding that of aluminum in 1960. No definite relationship was found between the volume of percolating water and the removal of the foregoing elements with it.

The quartz sands on which the soils studied developed do not contain soluble salts and the source of the water-soluble salts removed by percolation is the organic substance produced by higher plants and the dead organic substance decomposed by lower plants and soil and litter animals. If we express the amount of elements removed by percolation in percentages of the amount supplied by the fallen leaves, we will obtain indices which characterize the mobility of a corresponding element under given conditions (Table 8).

We constructed the following mobility series on the basis of such indices for 5 elements for which we had 7-year data:

1954 Ca > Al > K > Si > P
1955 Al > Ca > K > Si > P
1956 Al > Ca > K > Si > P
1957 Al > Ca > K > Si > P
1958 Ca > Al > K > Si > P
1959 Al > Ca > Si > P > K
1960 Ca > Si > Al > K > P

The sequence of the foregoing series is rather consistent. Only in 1954 and 1958 did Al and Ca change places, whereby the difference in the mobility of Al and Ca in 1958 was within the accuracy of the investigations. K changed places with Si and P in 1959. We did not find any explanation for the low mobility of potassium in 1959. In 1960 when percolation was at its lowest, the removal of silicon increased and that of aluminum decreased.

More detailed mobility series can be constructed on the basis of investigations in the last 3 years:

1958 Ca > Al > Mg > N > S > K > Si > P
1959 Al > Ca > Mg > Si > N > S > P > K

According to B. B. Bolynov the migration series is: S > Ca > Mg > K > P > Si > Al.

These mobility series differ essentially from the migration series in the weathering crust, compiled by Polynov (1). Aluminum, which is very mobile in the soil under an oak forest, is the least mobile in the Polynov series for the weathering crust. Potassium is more mobile in the weathering crust than in the soil studied. Phosphorus, which is the least mobile under soil conditions, occupies a central position of mobility in the series for the weathering crust. Sulfur, which is the most mobile in the migration series of Polynov, is not very mobile in the soil and is close to phosphorus with which it has a lot in common, from the biological point of view.

The difference between mobility series compiled on the basis of data on the release of elements during the mineralization of the oak forest litter and on their average removal by percolation is interesting:

Release from the litter: K > P > N = Mg > Ca > Si > Al
Removed by percolation: Al > Ca > Mg > N > K > Si > P

Potassium is removed from the plant residue most rapidly, but according to its removal beyond the soil profile it belongs to the least mobile elements. Aluminum, on the contrary, is very slowly released during the decomposition of the litter, but being released it acquires a relatively high mobility. The behavior of phosphorus and calcium shows similar differences.

The foregoing is caused by the fact that the solutions infiltrating into the soil from the forest litters change their composition in doing so, since the root systems of higher plants and microorganisms take up the elements selectively. A certain portion of the elements is retained because of the adsorption capacity of the soil. At the same time an increase in the content of elements is possible as a result of dissolution and exchange. This is somewhat similar to partition chromatography but complicated by biological processes. The soil is not an inert medium, and the solutions filtering through it undergo many changes in their composition and properties.

Since various formations draw into the biological cycle unequal amounts of elements and at different ratios, while soils differ from each other in their interaction with the infiltrating solutions, there is no basis to assume that there is only one series of mobile elements for all soils.

The influence of the nature of forest vegetation on the content of elements removed by percolation may be judged from the results of the analysis of the waters of forest streams. For this purpose we used streams with a small catchment basin, lying within the limits of an oak, aspen, or pine forest only. Beginning with 1955 we started with the chemical analysis of the water of such streams during the snow melting period. Now we have data for 6 years. We took the water of the Usmanka River for comparison (Table 9).

The analyses showed considerable fluctuations in the chemical composition of dissolved compounds in the streams from year to year. There was a certain parallelism between the fluctuations in the content of certain elements in the percolated water of the plots (Table 8) and that of the streams (Table 9). Thus, the highest amount of aluminum found in the

Table 9

Abbreviated results of the chemical analysis of water of temporary streams and the Usmanka River (Analyzed by M. K. Sviridova and M. Ye. Popova)

| Names of streams and rivers | Nature of watershed | Date | pH | Si | Al | Ca | K | P | S | N |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | In mg/liter | | | | | | |
| | 1955 | | | | | | | | | |
| Krutovskiy | Oak-covered | March 31 | — | 0,65 | — | 62,50 | — | 0,24 | — | — |
| Pridorozhnyy | Same | Same | — | 0 70 | — | 74,50 | — | 0,50 | — | — |
| Cherepakhinskiy | Aspen-covered | " | — | 0,70 | — | 44,35 | — | 0,24 | — | — |
| Usmanka River | Covered by a mixed-forest | March 30 | — | 0,84 | — | 30,24 | — | 0,22 | — | — |
| | 1956 | | | | | | | | | |
| Krutovskiy | Oak-covered | May 30 | 7,6 | 0,45 | 13,94 | 99,19 | 11,71 | Trace | — | 15,16 |
| Pridorozhnyy | Same | Same | 7,8 | 0,39 | 11,69 | 99,19 | 17,21 | " | — | 8,10 |
| Cherepakhinskiy | Aspen-covered | " | 7,5 | 0,37 | 13,97 | 63,71 | 12,91 | " | — | 6,95 |
| Usmanskiy | Pine-covered | " | 7,4 | 0,22 | 10,89 | 32,26 | 15,54 | " | — | 12,74 |
| Usmanka River | Covered by a mixed forest | " | 7.5 | 0,16 | 14,72 | 73,38 | 18,62 | " | — | 10,79 |
| | 1957 | | | | | | | | | |
| Krutovskiy | Oak-covered | April 9 | 7,0 | 1,70 | 21,72 | 24,12 | 5,08 | 0,06 | — | 3,36 |
| Pridorozhnyy | Same | " | 7,2 | 1,71 | 20,54 | 22,68 | 1,89 | 0,06 | — | 4,48 |
| Cherepakhinskiy | Aspen-covered | " | 7,2 | 1,80 | 16.53 | 11,88 | 0,70 | 0,05 | — | 5,60 |
| Usmanskiy | Pine-covered | April 11 | 6,7 | 1,61 | 12,30 | 6,48 | 1,01 | 0,07 | — | 4,48 |
| Usmanka River | Covered by a mixed-forest | April 12 | 6,6 | 1,69 | 12,30 | 11,52 | 0,50 | 0,06 | — | 6,72 |
| | 1958 | | | | | | | | | |
| Krutovskiy | Oak-covered | April 15 | 8,0 | 0,87 | 2,36 | 31,57 | 1,24 | 0,11 | 1,60 | 15,9 |
| Pridorozhnyy | Same | " | 8,0 | 0,81 | 2,37 | 18,42 | 1,49 | 0,03 | 0,72 | 14,9 |
| Cherepakhinskiy | Aspen-covered | " | 7,8 | 0,62 | 2,30 | 17,10 | 2,14 | 0,09 | 1,60 | 14,8 |
| Usmanskiy | Pine-covered | " | 6,0 | 0,58 | 2,42 | 8,04 | 1,14 | 0,09 | 2,40 | 15,1 |
| Usmanka River | Covered by a mixed-forest | " | 7,6 | 0,47 | 2,36 | 8,04 | 0,40 | 0,09 | 4,01 | 14,4 |
| | 1959 | | | | | | | | | |
| Krutovskiy | Oak-covered | April 4 | 7,0 | 11,40 | 0,18 | 26,46 | 0,36 | 0,01 | 0,33 | 1,34 |
| Pridorozhnyy | Same | " | 7,0 | 11,44 | 0,20 | 43,20 | 0,06 | 0,02 | 0,16 | 1,12 |
| Cherepakhinskiy | Aspen-covered | " | 7,6 | 8,19 | 0,18 | 10,80 | 0,17 | 0,01 | 0,01 | 1,57 |
| Usmanskiy | Pine-covered | April 5 | 6,6 | 7,89 | 0,19 | 12,26 | 0,09 | 0,01 | 0,30 | 1,60 |
| Usmanka River | Covered by a mixed-forest | " | 6,8 | 7,32 | 0,18 | 21,60 | 0,17 | Trace | 0,23 | 0,78 |
| | 1960 | | | | | | | | | |
| Krutovskiy | Oak-covered | April 15 | 7,4 | 8,15 | 0,31 | 17,91 | 0,47 | 0,15 | 0,60 | 4,45 |
| Pridorozhnyy | Same | " | 7,4 | 8,59 | 0,40 | 26,87 | 0,59 | 0,14 | 0,11 | 2,37 |
| Cherepakhinskiy | Aspen-covered | " | 7,5 | 7,39 | 0,46 | 13,74 | 0,59 | 0,18 | 0,11 | 13,24 |
| Usmanskiy | Pine-covered | April 16 | 7,0 | 6,57 | 0,38 | 6,18 | 0,82 | 0,16 | 0,48 | 8,80 |
| Usmanka River | Covered by a mixed-forest | April 15 | 7,5 | 5,48 | 0,43 | 13,90 | 0,41 | 0,17 | 0,27 | 2,37 |

Note: Comma represents decimal point.

percolation water from the plots in 1957 coincides with its highest amount in the water of the streams. The same is true of the highest content of calcium and potassium in 1956. In 1959 and 1960 the amount of silicon in the percolation water from plots and in the streams increased.

Stream water, fed from watersheds covered with various forests, differed essentially in calcium content. The water of streams with pine-covered watersheds was poor in calcium and had a more acid reaction than the water of streams fed from watersheds occupied by oak forests. The water streams from watersheds covered with aspen occupies an intermediate position. The reason for this difference is that more calcium is drawn into the biological cycle by an oak forest than by a pine forest. The reasons for the lesser removal of calcium from watersheds occupied by aspen is not clear, since the litter of an aspen forest has a somewhat higher calcium content.

The water of the Usmanka River is poorer in calcium than the water of streams in the oak forest, but richer than the water of streams in the pine forest. We must consider that the upper reaches of the Usmanka River lie partly in the steppe belt. Even though snow melting begins earlier in forest-free watersheds, they still have a certain effect on the composition of the water in the Usmanka River during the snow melting period in the forest.

We can see from the foregoing material that the nature of the forest litter formed in various forests affects not only the properties of soils developing in a forest, but also the composition of soil water feeding forest streams and rivers, and by the same token the composi-

tion of larger rivers. This relates the biological cycle of elements under various vegetation to the wider problem of the large geological cycle of substances in nature.

## Conclusions

1. The annual amount of foliage and litter in an oak forest undergoes considerable fluctuations depending on the weather conditions in individual years. Together with this the amount of nitrogen and ash elements entering the soil by way of leaf-fall changes.

2. The leaching of individual elements released during the decomposition of the litter in an oak forest takes place in the following order: $Fe < Al < Si < Ca < Mg = N < P < K$.

3. Part of the foregoing elements is selectively absorbed by living organisms and the solid phase of the soil during their percolation through the soil. The order in which the elements are removed by percolation differs from their order of removal from the forest litter. Potassium and phosphorus are especially clearly retained in the soil.

4. The water of streams having watersheds occupied by various types of forests differs considerably by content in dissolved salts. The water of streams fed from watersheds occupied by oak and aspen forests are richer in calcium salts than the water of streams with pine-covered watersheds.

5. The characteristics of the biological cycle of elements under various types of vegetation affect the composition of dissolved compounds in river waters, and, consequently, the large geological cycle of substances in nature.

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